NASA/CR-1998- 206716

Grant NAG3-1597
SwRI Project 15-6476
19 January 1998

A Final Report for

Participation in NASA TROPIX Science Team

7N-43-CR
OCT
1998
048 809

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INTRODUCTION

Grant NAG3-1597 provided support for Dr. James L. Burch of Southwest Research Institute to participate in the MIDEX-class definition of the TROPIX (Transfer Orbit Plasma Interaction Experiment) mission. TROPIX is both a scientific experiment and a flight demonstration of a solar electric propulsion space vehicle. The research supported by this grant resulted in the specific definition of magnetospheric and planetary science missions that can be uniquely implemented with SEP within the resources available in the MIDEX program. The proposed effort was primarily devoted to participation in meetings of the TROPIX Science Team. As a result of the preparation for, and discussions at, the TROPIX meetings, a plasma instrument suitable for inclusion on TROPIX was defined.

SCIENCE BACKGROUND

Solar electric propulsion (SEP) has great potential for use in unique new spacecraft missions to the Earth's magnetosphere as well as planetary magnetospheres and interplanetary space. The nearly continuous low thrust attained by SEP can be used to map out large regions of space in ways that cannot be implemented with conventional chemical propulsion. One of the most interesting and important applications of SEP is in the mapping of magnetospheric plasmas and fields from the lowest reaches of the Earth's magnetosphere (a few hundred kilometers) out to the magnetopause and beyond. The TROPIX mission was designed to achieve this objective. During its early phases, the TROPIX mission would map high-latitude electron and ion acceleration processes and the associated field-aligned currents as functions of altitude from about 400 km up to several thousand km. During the later phases of the mission, TROPIX would map plasmas and fields throughout the three-dimensional magnetosphere up to $> 10\ R_E$.

TROPIX MAGNETOSPHERIC MAPPING MISSION

A magnetospheric mapping mission uses the concept of changing orbits to sample a significant volume of the magnetosphere. This approach provides the ability to utilize the same science instruments throughout the magnetosphere, thereby simplifying the comparison of measurements from different regions under a wide range of conditions. There is the possibility of lingering in specific orbits or fine tuning them to maximize science return, moving to other plasma regions, or returning to repeat earlier observations for different conditions such as geomagnetic activity levels and seasons.

Much of the Earth's polar magnetosphere has not been characterized by in-situ measurements; the limited existing observations have generated as many new questions as answers. Polar missions have historically targeted one region for intensive study by single satellites (e.g., Hawkeye and Atmosphere Explorer) or attempted to use multiple spacecraft to make complementary in-situ measurements in different regions of the magnetosphere and ionosphere (e.g., Dynamics Explorer). Similar approaches have been taken in low-inclination missions such as the International Sun-Earth Explorer. There is significant science return to be gained from a mapping type mission that takes a single properly instrumented satellite and changes its orbit in a planned manner to study different polar altitude regions and processes throughout the magnetosphere. A magnetospheric mapping mission would take advantage of the orbit-change capability of SEP, starting at a low-altitude high-inclination orbit (400 km, > 60° inclination), spiraling outward in altitude in a nearly circular orbit, and eventually matching the shape of the dayside magnetopause. During the outward spiral, or perhaps a subsequent inward spiral, the inclination could be lowered to sample the largely unexplored equatorial magnetosphere.

Such a mission profile enables a study of the altitude dependence of auroral processes with the altitude remaining constant around an entire orbit, thereby sampling both polar hemispheres at two local times with an important parameter, altitude, remaining constant. At high inclinations this mission would examine the altitude profile of the polar cusps and map out the magnetopause boundary from the equator to the pole. At low inclinations it would examine the altitude dependence of substorm injection phenomena and track dayside reconnection phenomena as the magnetopause position moves inward or outward.

The TROPIX mission will provide a unique opportunity for mapping ion and electron acceleration phenomena in the polar ionosphere and magnetosphere by virtue of its low-thrust orbit-adjust capability, which will provide a continuously expanding circular orbit from altitudes of about 400 km up to as high as 10 R_E. The orbit inclination, which is planned to be initially in the range from 63° to 70° or higher, will be sufficient to sample the auroral regions, in which ionospheric ions and electrons are observed to be accelerated into upward-propagating beams, and primary aurora! electrons are accelerated downward into the atmosphere. Various plasma wave phenomena are observed to be associated with these accelerated particles, although cause and effect have not been clearly established.

An example of the phenomena that can be addressed in a unique way with TROPIX is the conical ion distribution or ion conic. Most observations from fixed-orbit spacecraft have indicated that the conics are produced by a wave-particle interaction, which accelerates ionospheric ions (generally H^+ and O^+) perpendicular to the local magnetic field. The magnetic mirror force subsequently converts the perpendicular energy to parallel energy, resulting in an upward moving distribution with ion velocity vectors lying along a conical surface centered on the magnetic field line. The narrow range of ion pitch angles that is observed indicates that the acceleration occurs in a restricted altitude range. An alternative explanation involves a wave-particle heating mechanism that directly produces a conical distribution and that operates over an extended range of altitudes. The type of altitude mapping that will be possible with TROPIX is the best way to determine which type of process (restricted in altitude or extended in altitude) is responsible for ion conics.

Similar altitude mapping opportunities exist for electron conics, ion beams, and auroral electron distributions as well as wave phenomena such as ion cyclotron waves, upper and lower hybrid waves, and auroral kilometric radiation, which are associated with or, in some cases, responsible for the observed particle acceleration. In addition, the field-aligned current Systems associated with the accelerated particles, which produce significant Joule heating of the upper atmosphere could also be mapped in altitude.

The charged particle and electromagnetic field instrumentation that should be included on TROPIX is as follows:

DC Magnetometer for measurement of field-aligned currents.

- AC Magnetometer (10 Hz to 50 kHz)
- AC Electric Field Instrument (DC to 1 MHz)
- Electron Spectrometer (3D distribution functions from 1 eV to 50 keV)
- Ion Mass Spectrometer (3D mass-resolved distribution functions from 1 eV to 50 keV)
- Energetic Particle Spectrometer (50 keV to 1 MeV electrons; 50 keV to 10 MeV ions)

The instrumentation defined in this project included the Electron Spectrometer and the Ion Mass Spectrometer. This instrumentation is referred to as MOSS (Miniaturized, Optimized Space Sensor).

MOSS INSTRUMENT DESCRIPTION

The Miniaturized, Optimized Space Sensor (MOSS) for the TROPIX spacecraft is based on an instrument that has been developed under the sponsorship of the SwRI Internal Research program. It is the basis for the Ion and Electron Spectrometer (MOSS) for the Rosetta mission. As presently designed, this instrument will meet all of the TROPIX mission's plasma science objectives.

The MOSS is an electrostatic analyzer, featuring electrostatic angular deflection to obtain a field of view of 90° (azimuth) × 360° (polar angle). The azimuthal field of view is electrostatically segmented into 5° elements, while the polar angle is segmented by a position-sensitive anode into 22.5° elements. The instrument objective is to obtain ion and electron distribution functions over the energy range extending from 1 eV/e up to 30 keV/e, with a basic time resolution of 3 s. Table 1 lists the complete set of MOSS performance parameters and its resource requirements. The instrument operational concept is illustrated in Figure 1. The back-to-back top hat geometry of the MOSS electrostatic analyzer allows it to analyze both electrons and positive ions with a single entrance aperture. The drawing in Figure 1 has cylindrical symmetry about the vertical axis passing through its center. The MOSS top hat analyzers have toroidal geometry with a smaller radius of curvature in the deflection plane (the plane of Figure 1) than in the orthogonal plane. This toroidal feature results in a flat deflection plate geometry at the poles of the analyzers and has the advantage that the focal point is located outside the analyzers rather than within them, as is the case with spherical top hat analyzers. In addition, the MOSS entrance aperture contains electrostatic deflection electrodes, which expand its azimuthal angle field of view to ±45°. With the typical top hat polar-angle field of view of 360°, the MOSS acquires a total solid angle of 2.8π steradians.

Ions and electrons approaching the MOSS first encounter a toroidal-shaped grounded grid encircling the instrument (see Figure 1). Once inside the grid the electric field produced by bipolar electrodes deflects ions and electrons with a range of energies and azimuthal angles into a field-free entrance aperture containing serrated walls to minimize scattering of ultraviolet light and charged particles into the instrument. The particles then enter the top hat region and the electric field produced by the flat electrostatic analyzer segments of the ion and electron analyzers. Particles within a narrow 4% energy passband will pass through the analyzers and be focused onto conversion dynodes. The selected energy will correspond to a particular 5° azimuthal entrance angle, depending on the ratio of voltages on the angle deflectors and the electrostatic analyzers (ESAs). Secondary electrons produced on the conversion dynodes are focused on the electron and ion MCPs, which produce charge pulses on 16 discrete anodes, which define the polar acceptance angles. The pulses from the segmented MCPs are amplified by charge-sensitive pre-amplifiers (CSPs) and recorded in the 16 × 24 bit ion and electron counters. The data are buffered before being sent to the output serial register for transmission to the spacecraft data processor as serial telemetry packets. The stepping sequences of the angle and energy deflection voltages of the instrument are determined by the modes of operation.

Parameter	Value
Energy: Range	3 eV/e to 30 keV/e
Resolution	0.05
Scan	Stepped, Mode Dependent
Angle: Range (FOV)	90° x 360° (2π sr)
Resolution	5° x 22.5° (18 azimuthal x 16 polar)
Mass Composition:	
Range	1 to 60 amu/e
Resolution	$M/\Delta M \sim 4$ (fwhm)
Temporal Resolution:	
2D Distribution	32 ms
3D Distribution	65 ms
Geometric Factor:	
Per Azimuthal Angle Sector (total ions)	10^{-3} cm^2 sr eV/eV
Per Azimuthal Angle Sector (ion composition)	10^{-4} cm^2 sr eV/eV
Per Azimuthal Angle Sector (electrons)	10^{-3} cm^2 sr eV/eV counts/electron
Mass	3900 g
Power	7.7 W
Dimensions	15.2 × 15.2 × 27.0 cm
Downlink Data Rate	250 to 10,000 bps

Table 1. MOSS performance parameters and resource requirements

Software Description

The MOSS instrument contains a single micro-controller (RTX20X10) that communicates with the spacecraft, transmits the collected science data, and monitors the instrument status. The flight software is written in the C and Forth programming languages.

The MOSS data processor stores and re-transmits the data stream that the instrument produces. Other than data compression, no special data handling is required. The data processor

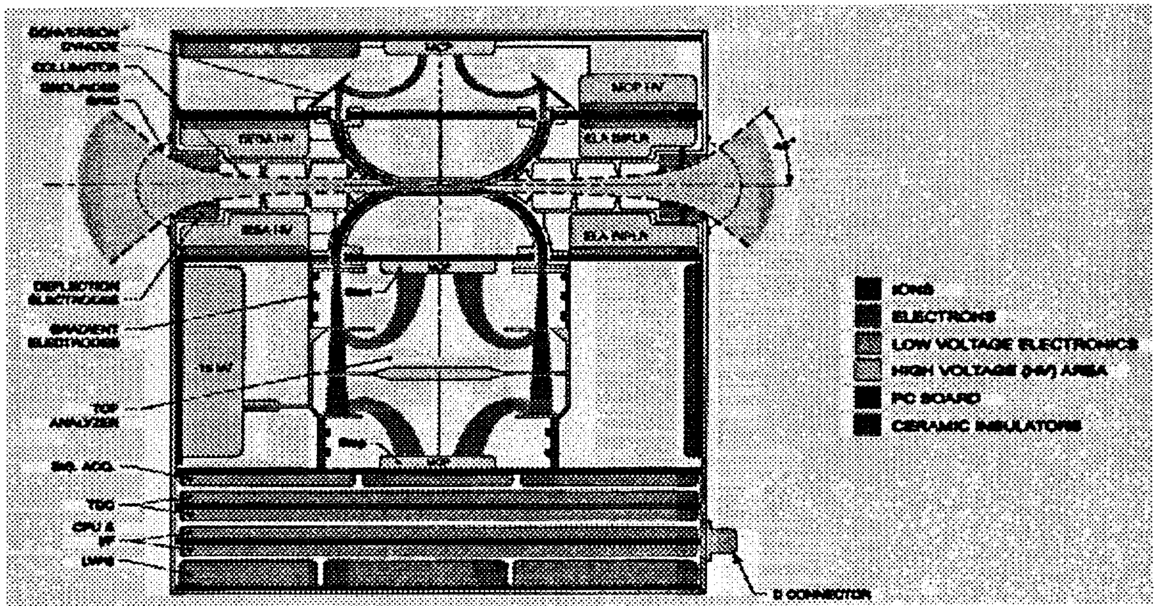

Figure 1 MOSS cross-sectional view

stores time-tagged commands so that a sequence of commands can be performed when the spacecraft is not in direct contact with the ground-stations.

Operational Modes

The MOSS has several operational modes. The instrument is always brought up first in the Initialization Mode to ensure that all commanded states are in safe, nominal ranges. After initialization, the Low-Voltage Checkout Mode is entered, and all low-voltage circuitry completes a self-test. Next the High-Voltage Checkout Mode is used to step the high-voltages up to operational levels while closely monitoring all currents for nominal operation. If the high voltage circuitry is turned off, the low-voltage checkout mode is run before the high voltage is brought up again. Science Mode 1 is a baseline science mode, which provides a comprehensive data set on a default basis. From Science Mode 1, other modes such as the Survey Mode, Region-of-Interest Mode, and Snapshot Mode can be entered for focused studies of auroral plasma. In addition, with the MOSS in Science Mode 1, two different engineering modes can be run in the background in order to monitor different housekeeping functions.

A minimum of elective instrument commanding is anticipated. The main choices within the realm of science operations will involve (1) choosing from a finite selection of pre-defined science data products and (2) managing the instrument high voltage. Internal constraints on operations are imposed by considerations which fall into two categories: those which have an immediate science or data impact and those which have a hardware safety impact. This latter category is critical at any time, while the criticality of constraints imposed by consideration of data impacts is highly variable. Primary safety-related constraints on operations involve (1) high-voltage operation and (2) MCP current limitation.

Consideration of high-voltage operation requires not only proper design and assembly, but also the proper level of vacuum and history at vacuum prior to operating at high voltage either on the ground or in space. MCP current limitation is required because of the negative temperature coefficient of MCPs. Excessive count rates can lead to unstable MCP current and local thermal catastrophe.